A lifetime prediction model for single crystal superalloys subjected to thermomechanical creep-fatigue-oxidation damage

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A LIFETIME PREDICTION MODEL FOR SINGLE CRYSTAL SUPERALLOYS SUBJECTED TO THERMOMECHANICAL CREEP-FATIGUE-OXIDATION DAMAGE

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ABSTRACT

This paper contains a brief description of a lifetime prediction model for Single Crystal Superalloys operated at high temperatures and subjected to creep, fatigue and oxidation damage mechanisms. The model aims at predicting engineering life to crack initiation and describing dominating damage mechanisms and their non-linear interaction in such materials. Microcracks propagation from initial casting pores is considered as the critical life-limiting factor. The initial damage, before any type of loading, is therefore quantified with the help of pores' statistical distribution. Microcracks propagation is described through creep-fatigue interaction under globally elastic or plastic material behaviors. Interaction of surface oxidation with creep-fatigue damage is described as drop of material strength within and beyond the oxidized zone. Different model parameters are obtained directly from materials tensile, creep and LCF test data at different temperatures. Some parameters, independent of temperature, are fitted on a large variety of LCF test data. Another set of LCF and TMF test data has been used to compare model predictions with. As a validation test of model prediction capabilities, lifetime of numerous LCF and TMF tests with various cycle shapes and on different material orientations has been calculated to a significant level of accuracy. Another validation test reported in here is the surface crack growth measured on the specimens and predicted accurately through this model.

1 INTRODUCTION

Thermomechanical creep and fatigue are among the major life limiting factors for aeronautical or land based gas turbines. In turbo-machinery industry, lifing of turbine parts is usually based on simple but robust semi-empirical methods, which are constantly evaluated and validated against field experience. However, need is being felt to use material specific lifing methods, which cater for specific failure mechanisms of a particular type of material. Methods, which are fairly accurate, are flexible and are not limited to one type of loading cycle.

In aeronautical as well as in land based axial turbines, blades are now widely made of nickel based single crystal superalloys. These materials are optimized for creep resistance but are prone to oxidation attack at high temperatures. This is the reason why in certain cases, the turbine blades are coated with protective materials. A predominant source of failure in these materials remains, however, the internal pores resulting from the solidification process. A physical model, in case of single crystal superalloys, should take into account the presence of internal pores and the propagation of internal cracks originating at these pores. The lifetime prediction model developed herein incorporates this physical aspect of single crystal failure. Damage is considered to be the ratio of the cracked surface to the total surface of the most critical section. Its evolution is ensured by the propagation of cracks originating from material casting defects. An internal pore near the surface of the component can propagate outwards through the material and give rise to a surface crack. A probabilistic analysis is carried out in order to determine the number and size of casting pores present in a given volume of material.

Another particularity of Ni-based SX superalloys is their constitutive and damage anisotropy. The anisotropy of these face-centered cubic materials is therefore considered in this model in the following way: stresses applied to a given volume of material are resolved onto all octahedral ({111} <011>) and cubic ({001}<011>) slip systems. The damage equations are then applied on slip systems themselves using resolved shear and normal stresses on every slip system. Material parameters chosen in the model are obtained from uni-axial material data generated on <001> and <111> specimens. Material properties thus obtained are considered to be intrinsic properties of octahedral and cubic slip systems respectively. Any other combination of loading and crystal orientation can then be reduced to shear and normal stresses applied on active slip systems.

2 DAMAGE MODELING

The lifetime prediction model presented here is formulated in the general framework of Damage Mechanics, see e.g. Chaboche [1], a preliminary version of the model was previously given in [2]. Damage variable is identified as the ratio of cracked surface area to the total surface area of a critically loaded zone. This definition of damage leads to a scalar damage variable D with a real physical significance. D is defined in eqn (1):

$$D = \frac{S_{cracked}}{S_{total}}\ ,\ \ \frac{dD}{dt} = f(\sigma, T, N, D_0)\ . \tag{1}$$

where S denotes surface area; T, σ applied temperature and stress, N number of cycles of loading, and D_0 initial damage. Consequently, the locally applied stress is increase by damage increase, eqn (2).

$$\tilde{\sigma} = \frac{\sigma}{1 - D} \tag{2}$$

where $\tilde{\sigma}$ is defined as an effective stress, function of D.

2.1 Characteristic Microstructural Element

Damage grows as the initial material pores (damage D_0) start to grow under the influence of creep and fatigue. Damage growth consists of successive failure of characteristic microstructural elements in which damage can accumulate before reaching a critical value. The concept of characteristic microstructural elements is of fundamental importance because it helps simplifying the passage of failure description from that of a test specimen failure, to the one in a complex geometry part. If the failure of a test specimen can be successfully modeled with the help of failure of successive microstructural elements, then that of a small zone in a complex part can also be described by successive failures of microstructural elements. In this model the characteristic microstructural element is modeled as a cube of side L and the volume L^3 corresponds to that of a secondary dendrite of SX superalloy.

2.2 Modeling of Material Pores

Since the damage growth is defined as that of the initial material defects i.e. casting pores, these latter must be modeled based on observations. Material pores distribution in Figure 1 was determined through metallographical observations by [3] on CMSX4 SX superalloy. In reality, the pores are of random irregular shapes but for the sake of simplicity the encircling diameter of pores was measured and reported by [3].

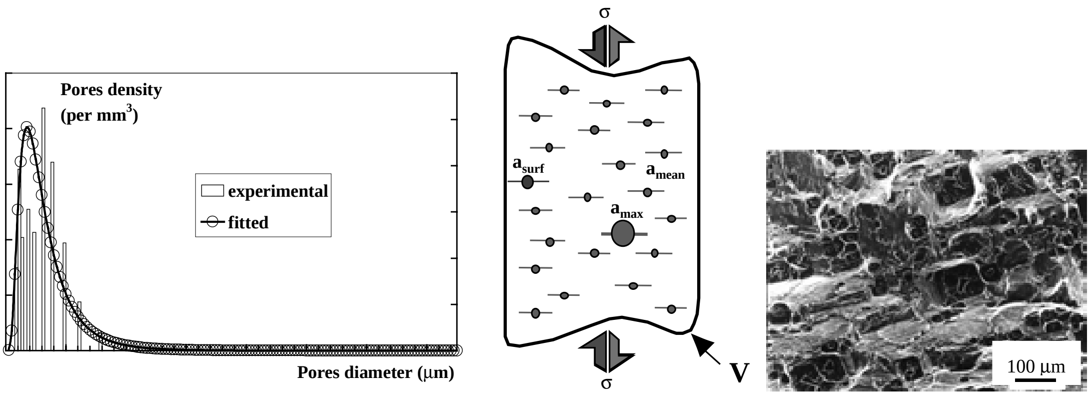

Figure 1. Schematic description of pores distribution modeling. On the right hand side, a fracture surface of CMSX4 LCF test at 950°C, cracks propagation from casting pores is conspicuous.

The distribution of material pores is modeled on the basis of three type of pores (see Figure 1 the middle diagram) i.e. mean size pore uniformly distributed over the entire volume, the largest pore within a given volume and the largest pore in the sub-surface zone. This latter is responsible for a single surface crack initiation.

2.3 Damage Equations

In order to describe the growth of cracks from material pores, the following fatigue and creep damage equations are used:

2.3.1 Fatigue and Creep Damage Equations

At high temperatures and under tensile stress conditions, micro-cracks can also propagate due to creep.

$$da = da_{fatigue} + da_{creep} \tag{3}$$

Depending upon the applied stress range, fatigue crack growth can take place in globally elastic or plastic material behavior. Therefore two different crack propagation regimes are used in parallel. One is denoted here as Basquin's crack propagation regime and the other one as Tomkins' crack propagation regime.

$$da_{fatigue} = max < da_{Basquin} : da_{Tomkins} > \tag{4}$$

Basquin's relation caters for stress controlled crack propagation regime under globally elastic material behavior. In terms of resolved shear stresses, it can be written as in eqn (5).

$$\frac{\Delta\tilde{\tau}_s}{2} \cdot N^b = \tau_f \text{ where } \Delta\tilde{\tau}_s = \frac{\Delta\tau_s}{1-D} \tag{5}$$

$\Delta\tau_s$ is the resolved shear stress range on a given slip system and τ_f is critical fatigue shear strength of the material on either cubic or octahedral slip system. If N_L is the number of cycles required to fail a unit microstructural element of side L, the crack growth rate is:

$$\frac{da}{dN} = \frac{L}{N_L} \tag{6}$$

This relation can be used to determine the crack propagation rate under the Basquin's regime, eqn (7):

$$\frac{da}{dN} = \frac{L}{n} \cdot \sum_s \left[\frac{\Delta\tilde{\tau}_s}{2 \cdot \tau_f} \right]^M \tag{7}$$

where $M = 1/b$, n is the total number of slip systems considered in calculations.

Tomkins' equation allows calculating crack growth rate under generalized plasticity condition in polycrystalline materials [4]. This equation is therefore rewritten using shear stress and strain components on slip systems:

$$\frac{da}{dN} = \sum_s B_s \cdot a \text{ , and } B_s = \left[\frac{1}{cos(\frac{\pi}{2} \cdot \frac{\Delta\tilde{\tau}_s}{2 \cdot \tau_f})} - 1 \right] \cdot \Delta\gamma_s \tag{8}$$

$\Delta\gamma_s$ is the applied shear strain range on a particular slip system s and a is the current crack length. For creep crack growth, classical continuum damage mechanics approach of Rabotnov [5] is used. According to this approach the creep damage rate for a given slip system can be described as:

$$dD_{creep} = (1-D)^{-k_s} \left[\frac{\tilde{\tau}_s}{A_s} \right]^{r_s} dt \tag{9}$$

where r_s, k_s and A_s are material parameters associated with either cubic or octahedral slip systems.

2.3.2 Oxidation Damage Equations

Interaction of creep-fatigue with oxidation results in accelerated crack propagation for cracks exposed to ambient air. It is found in experience that oxidation of material gives rise to a brittle zone greater in size than the actually oxidized zone. This embrittled zone manifests lower strength than the non-oxidized material. The drop in material's strength due to oxidation is therefore taken in account in this model. This procedure has already been described in some detail for polycrystalline superalloys in cast and wrought forms [6-8]. The depth of the embrittled zone l_f is supposed to be proportional to the oxidized depth l_{ox} (with a constant ratio P). The kinetics of oxidation in the interdendritic zone of single crystal superalloys, as in polycrystalline material [9] follows a power relation with time, presented in eqn (10).

$$dl_{ox}^4 = \alpha^4 \cdot dt \text{ and } \alpha^4 = \alpha_0^4 \cdot \left[1 + \left(\frac{\Delta\varepsilon_p}{2\varepsilon^*} \right)^2 \right] \tag{10}$$

Eqn (10) can be integrated over the time of a cycle to calculate the length of an oxidation spike. α is called the oxidation coefficient, which depends upon the nature of material and on the range of plastic deformation. Eqn (10) uses a relation suggested by [9] for a polycrystalline Ni-based superalloy, Udimet 720, to describe the influence of plastic deformation on the oxidation coefficient α. α_0 is characteristic oxidation coefficient of a material and ε^* is a parameter, which defines the extent of interaction between the plastic strain range and the oxidation. For a single crystal case $\Delta\varepsilon_p = \sum_s m_s \cdot \Delta\gamma_p^s$ which is the resultant of plastic shear strain components on all slip systems of a family (cubic or octahedral), in the direction of the highest principle stress component. The strength of the brittle zone is defined in eqn (11):

$$\tau_{cf} = \tau_c \cdot \beta \tag{11}$$

where τ_{cf} is strength of the brittle zone and β is called as embrittlement factor which is less than 1 and depends upon temperature and the nature of the material.

3 RESULTS

This section presents some results of the application of this model on lifetime prediction of LCF and TMF test specimens in CMSX4 and AM1 SX superalloys. Tests lifetime under various cycle shapes, loading conditions and material orientations have been calculated using the same set of equations and model parameters.

3.1 Prediction of Lifetime over a Wide Range of Test Frequencies

Figure 2 presents comparison of experimental cyclic lifetime of AM1 SX test specimens at 950°C to the one calculated through the model. Two test cases presented are that of LCF cycles with 0.05Hz and 20Hz. A good correlation has been achieved. Figure 2 also shows lifetime prediction for different SX orientations specimens. Despite large scatter in test results, an overall good correlation was achieved.

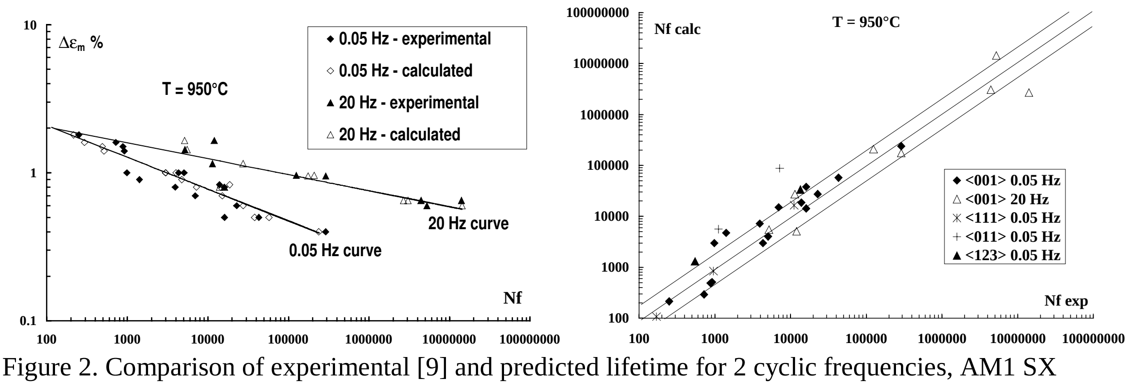

Figure 2. Comparison of experimental [9] and predicted lifetime for 2 cyclic frequencies, AM1 SX

3.2 Prediction of Lifetime over a Wide Range of Temperatures and Dwell Time

Figure 3 shows the creep-fatigue lifetime prediction capability of the model with the help of two graphs. The right-hand side graph shows the experiment-calculation comparison for CMSX4 from 20°C to 850°C. The left-hand side graph is for 950°C and shows the prediction capability of the model for dwell periods ranging from none to 30 minutes.

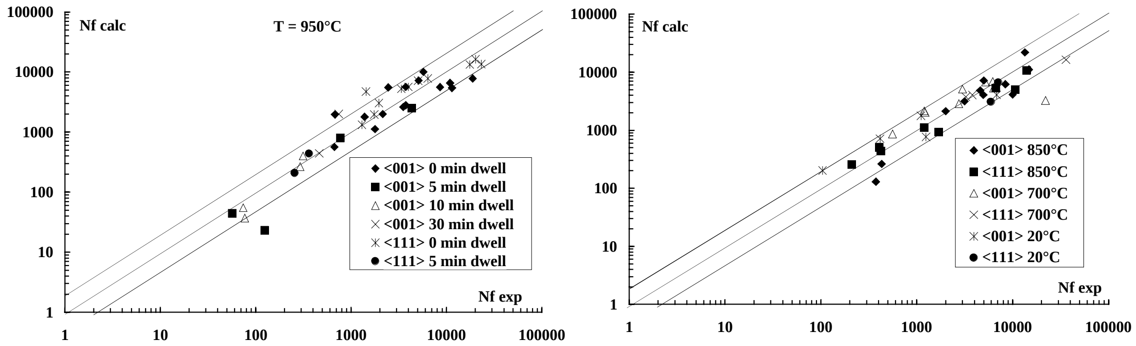

Figure 3. Comparison of experimental [2, 3] and predicted lifetime of CMSX4 SX specimens.

3.3 Prediction of TMF Lifetime for Various Cycle Shapes

Figure 4 shows the TMF lifetime prediction capabilities of the model. On the left-hand graph are shown different TMF test cycles applied to AM1 SX specimens. These cycles contain more than one slope and lead to different lifetime values under the same applied strain range. The right-hand graph shows the comparison of experimental and calculated values. A good correlation is achieved.

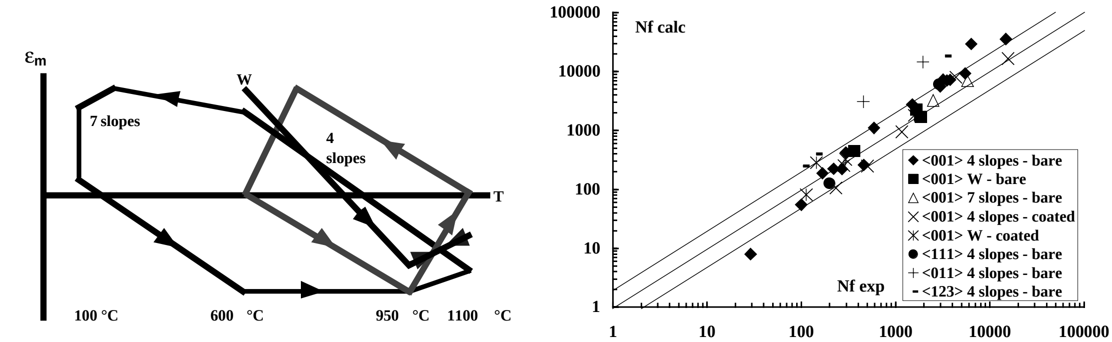

Figure 4. Prediction of TMF test results for AM1 SX specimens, tested [10] with different TMF cycles.

3.4 Prediction of TMF Surface Crack Growth

As a complementary validation criterion for the model lifetime prediction capabilities on simple geometry test specimens, prediction of surface crack growth rate was carried out.

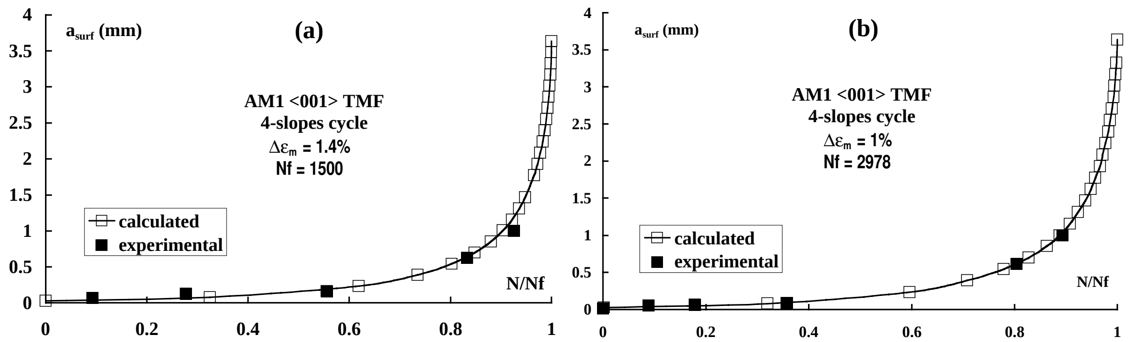

Figure 5. Prediction of measured surface crack growth [10,11] during TMF tests on AM1 SX specimens.

Figure 5 shows a comparison of experimentally measured surface crack length as a function of relative cyclic life with the one calculated through this model. An excellent correlation can be seen in the presented graphs.

4 CONCLUSIONS

- A lifetime prediction model is developed for single crystal superalloys. This model can be used to predict lifetime under thermo-mechanical creep-fatigue loading and oxidation damage
- Damage propagation is defined as the growth of the micro-cracks originating from casting defects. These cracks can grow due to creep-fatigue-oxidation conditions.
- Model predicts well the isothermal and thermo-mechanical creep-fatigue lives of AM1 and CMSX4 single crystal superalloys specimens for wide ranges of temperature, SX orientations, cycle shapes and frequencies.
- Experimentally measured surface crack growth curves of TMF tests on AM1 SX superalloy, have been satisfactorily predicted using this model.

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